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Letter to the Editor

Detection of very-high energy γ-ray emission from NGC 1275 by the MAGIC telescopes

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ABSTRACT

We report on the detection of very-high energy (VHE, $E > 100$ GeV) γ-ray emission from NGC 1275, the central radio galaxy of the Perseus cluster of galaxies. The source has been detected by the MAGIC telescopes with a statistical significance of 6.6 σ above 100 GeV in 46 hr of stereo observations carried out between August 2010 and February 2011. The measured differential energy spectrum between 70 GeV and 500 GeV can be described by a power law with a steep spectral index of $\Gamma = -4.1 \pm 0.7_{stat} \pm 0.3_{syst}$, and the average flux above 100 GeV is $F_\gamma = (1.3 \pm 0.2_{stat} \pm 0.3_{syst}) \times 10^{-11}$ cm^{-2} s^{-1}. These results, combined with the power-law spectrum measured in the first two years of observations by the *Fermi*–LAT above 100 MeV, with a spectral index of $\Gamma \simeq -2.1$, strongly suggest the presence of a break or cut-off around tens of GeV in the NGC 1275 spectrum. The light curve of the source above 100 GeV does not show hints of variability on a month time scale. Finally, we report on the nondetection in the present data of the radio galaxy IC 310, previously discovered by the *Fermi*–LAT and MAGIC. The derived flux upper limit $F_\gamma^{U.L.}(> 300\ \mathrm{GeV}) = 1.2 \times 10^{-12}$ cm^{-2} s^{-1} is a factor ~ 3 lower than the mean flux measured by MAGIC between October 2009 and February 2010, thus confirming the year time-scale variability of the source at VHE.

Key words. galaxies: active — galaxies: jets — galaxies: individual (NGC 1275) — galaxies: individual (IC 310) — gamma rays: galaxies

1. Introduction

NGC 1275 ($z = 0.0179$), the central dominant galaxy of the Perseus cluster, harbors one of the closest active galactic nuclei (AGN), already included in the original Seyfert list (Seyfert, 1943). The AGN is a very bright radio source showing an extended jet with Fanaroff-Riley I morphology (e.g. Vermeulen et al., 1994; Buttiglione et al., 2010). The optical emission of the nucleus is variable and strongly polarized from 3% to 6% (Maza, 1979; Martin et al., 1983), implying that the relativistic jet contributes significantly to the optical continuum (Angel & Stockman, 1980). The source has also been classified as a BL Lac object (Veron, 1978). However, the jet increases its inclination from 10° to 20° on milliarcsecond scales

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up to 40° to 60° at arcsecond scales (Krichbaum et al., 1992). Due to its brightness and proximity this source is ideally suited to study the physics of relativistic outflows and the "feedback" effects of the jet on the cluster environment (e.g. Fabian et al., 2008; Gallagher, 2009).

In fact, NGC 1275 is one of the closest γ-ray emitting AGN. It was first unambiguously detected in the high-energy (HE, 100 MeV $< E <$ 100 GeV) γ-ray range by the *Fermi* Large Area Telescope (LAT) (Abdo et al., 2009), during the first four months of *all-sky-survey* observations, with an average flux above 100 MeV of $F_\gamma = (2.10 \pm 0.23) \times 10^{-7}$ cm^{-2} s^{-1}. The differential energy spectrum between 100 MeV and 25 GeV was described well by a power law with a spectral index of $\Gamma = -2.17 \pm 0.05$. While no variability was observed during these four months of observations, subsequent results based on the first year of *Fermi*–LAT observations (Kataoka et al., 2010) show evidence of flux variability on time scales of months. Furthermore, the average γ-ray spectrum show a significant deviation from a simple power law, indicating an exponential cut-off at the break photon energy of $E_c = (42.2 \pm 19.6)$ GeV.

More recently, the results obtained from the first two years of *Fermi*–LAT observations (Brown & Adams, 2011) have given clear evidence for variability on time scales of days above 800 MeV, revealing that several major flaring events occurred during the two-year observation period. A harder-when-brighter correlation between flux and spectral index was also found. Brighter and therefore harder > GeV states are then promising for triggering observations at very high energy (VHE, $E >$ 100 GeV). Finally, present upper limits at VHE provided by MAGIC-I (Aleksić et al., 2010a) and VERITAS (Acciari et al., 2009) combined with the *Fermi*–LAT results mentioned above suggested that NGC 1275 may have a break or cut-off in the spectrum around tens of GeV.

The Perseus galaxy cluster contains another γ-ray source, the radio galaxy IC 310, located at $\sim 0.6°$ from NGC 1275. It was discovered in 2010 by the *Fermi*–LAT in the 30 GeV – 300 GeV energy range (Neronov et al., 2010) and for energies > 260 GeV by MAGIC (Aleksić et al., 2010b). The combined MAGIC and *Fermi*–LAT spectrum is consistent with a flat spectral energy distribution (SED) stretching without a break over more than three orders of magnitude in energy (2 GeV – 7 TeV). The spectrum at VHE measured by MAGIC has a spectral index of $\Gamma = -2.00 \pm 0.14$, and the mean flux above 300 GeV, from October 2009 to February 2010, was $F_\gamma = (3.1 \pm 0.5) \times 10^{-12}$ cm^{-2} s^{-1}. Strong hints of a week to a year time-scale variability were seen in the MAGIC data.

In this letter we present the results of the observations of NGC 1275 at VHE performed with the MAGIC telescopes between August 2010 and February 2011, which resulted in the first detection of the source above 100 GeV. The same observational campaign also provided results on the variability at VHE of IC 310. This letter is accompanied by a separate paper dedicated to the study of the Perseus cluster environment, focusing on possible VHE γ-ray emission induced by cosmic rays (Aleksić et al., 2011b). The multiwavelength emission of NGC 1275 from radio to VHE will be addressed in future work.

2. Observations and analysis

The MAGIC system consists of two 17 m dish Imaging Air Cherenkov Telescopes (IACTs) located at the Roque de los Muchachos observatory, in the Canary Island of La Palma (28.8°N, 17.8°W, 2200 m a.s.l.). Since late 2009 the telescopes are working in stereoscopic mode providing an excellent sensitivity of $<$ 0.8% of the Crab flux (C.U.)[1] for energies above $\sim$ 300 GeV in 50 hr of observations (Aleksić et al., 2011a) and a trigger energy threshold of 50 GeV, which is the lowest among the existing IACTs. The MAGIC telescopes are currently the most sensitive instrument between 50 GeV and 200 GeV, allowing us to extend up to the TeV scale the observations carried out by the *Fermi*–LAT.

The Perseus galaxy cluster region was observed by the MAGIC telescopes during two campaigns. The first one was carried out between October 2009 and February 2010, for a total observation time of 45.3 hr. This survey resulted in the discovery of the radio galaxy IC 310 as VHE emitter (Aleksić et al., 2010b). The latest campaign (total observation time of 53.6 hr), which resulted in the detection of NGC 1275 at VHE presented in this letter, was performed between August 2010 and February 2011. The source was observed in the wobble mode (Fomin et al., 1994), with data equally split in four pointing positions located symmetrically at 0.4° from NGC 1275, in order to ensure optimum sky coverage and background estimation. The survey was carried out during dark time at low zenith angles (from 12° to 36°), which guaranteed the lowest energy threshold ($\sim$ 50 GeV).

The data analysis was performed using the standard MAGIC software package (Albert et al., 2008b; Aliu et al., 2009), taking advantage of newly developed stereoscopic analysis routines (Moralejo et al., 2009; Aleksić et al., 2011a; Lombardi et al., 2011). The analysis cuts applied to NGC 1275 data were optimized by means of contemporaneous Crab Nebula data and Monte Carlo (MC) simulations.

After the application of standard quality checks, 7.9 hr of data were rejected mainly due to nonoptimal atmospheric conditions. The selected sample used for deriving the results presented here is therefore composed by 45.7 hr of good quality stereo data.

3. Results

The θ^2 distributions[2] with respect the signal region and the background (estimated from 3 distinct regions), for energies above 100 GeV, are shown in Fig. 1. We found an excess of 522 ± 81 events, corresponding to a significance of 6.6 standard deviations (σ), calculated according to the Eq. 17 of Li & Ma (1983). It is worth noting that the background estimation is not affected by a possible IC 310 γ-ray contribution, since the latter source was not detected in the present data.

The NGC 1275 differential energy spectrum measured by MAGIC between 70 GeV and 500 GeV can be described by a simple power law ($\chi^2/n_{dof} = 0.76/1$)

$$\frac{\mathrm{d}N}{\mathrm{d}E} = (3.1 \pm 1.0_{stat} \pm 0.7_{syst}) \times 10^{-10} \left(\frac{E}{100\ \mathrm{GeV}}\right)^{\Gamma}, \qquad (1)$$

in units of cm^{-2} s^{-1} TeV^{-1}, with $\Gamma = -4.1 \pm 0.7_{stat} \pm 0.3_{syst}$[3]. The mean flux above 100 GeV is $F_\gamma = (1.3 \pm$

[1] In this letter C.U. stands for Crab units, defined as the fraction of the Crab Nebula flux given in Eq. 1 of Aleksić et al. (2011a), which corresponds for energies above 100 GeV to 5.4×10^{-10} cm^{-2} s^{-1}.

[2] The θ^2 is the squared angular distance between the arrival direction of the events and a given nominal position (e.g. Daum et al., 1997).

[3] The systematic errors of the flux normalization and the energy spectral slope considered here have been estimated to be 23% and ±0.3, respectively, whereas the systematic error on the energy scale is 17%. These values are more conservative than those presented in Aleksić et al. (2011a), given the flux weakness and the spectral steepness of NGC 1275, as measured by MAGIC.

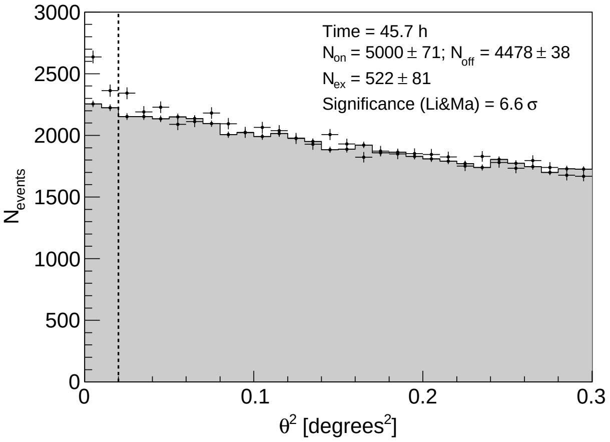

Fig. 1. θ^2 distributions of the NGC 1275 signal and the background estimation from 45.7 hr of MAGIC stereo observations taken between August 2010 and February 2011, above an energy threshold of 100 GeV. The region between zero and the vertical dashed line (at 0.02 degrees^2) represents the signal region.

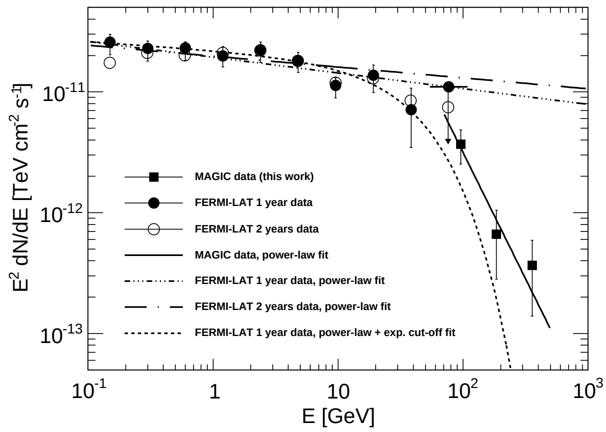

Fig. 2. NGC 1275 spectral energy distribution measured by MAGIC between 70 GeV and 500 GeV (filled squares), together with the results above 100 MeV achieved from the first year (filled circles, Kataoka et al., 2010), and from the first two years (open circles, Brown & Adams, 2011) of the *Fermi*–LAT *all-sky-survey* observations. The power-law fits to the *Fermi*–LAT data (extrapolated up to 1 TeV) are also shown, together with the exponential power-law fit provided in Kataoka et al. (2010).

$0.2_{stat} \pm 0.3_{syst}) \times 10^{-11}$ cm^{-2} s^{-1}, corresponding to $(2.5 \pm 0.4_{stat} \pm 0.6_{syst})$% C.U. The steepness of the spectral index measured by MAGIC strongly supports the presence of a break or cut-off in the NGC 1275 spectrum around tens of GeV, as already suggested by the *Fermi*-LAT results (Kataoka et al., 2010; Brown & Adams, 2011), and is consistent with the upper limits on the flux at VHE provided by MAGIC-I (Aleksić et al., 2010a) and VERITAS (Acciari et al., 2009). The rapid decline in the spectrum, which causes the NGC 1275 signal to vanish above approximately 500 GeV, permits investigating possible VHE γ-ray emissions induced by cosmic rays in the Perseus cluster environment above that energy (Aleksić et al., 2011b).

In Fig. 2, the SED measured by MAGIC is compared with the results in the 100 MeV – 100 GeV range provided by the *Fermi*–LAT, averaging *Fermi* data over the first year (Kataoka et al., 2010) and the first two years (Brown & Adams, 2011). The comparison suggests that a significant spectral steepening occurs around $\sim$ 100 GeV. However, the present non-simultaneous data do not allow discussing whether the spectral change corresponds to a break between two power laws or exponential cut-off.

The August 2010 to February 2011 light curve of NGC 1275 computed for an energy threshold of 100 GeV and with a monthly binning is shown in Fig. 3. No evidence of variability can be derived from these measurements. In fact, fitting the light curve with a constant flux hypothesis yields a $\chi^2/n_{dof} = 7.4/6$, corresponding to a probability $P(\chi^2) = 0.29$.

The significance skymap of the central region of the Perseus cluster above 100 GeV is shown in Fig. 4. A hot spot at $> 6\ \sigma$ significance level consistent with the sky position of NGC 1275 is present. The position of the radio galaxy IC 310 is also shown. No significant excess events coming from IC 310 have been found in the observations presented here. The corresponding integral flux upper limit above 300 GeV (performed using the Rolke et al., 2005 method, with a confidence level of 95%, and a total systematic uncertainty of 30%) is $F_\gamma^{U.L.}(> 300\text{ GeV}) = 1.2 \times 10^{-12}$ cm^{-2} s^{-1}, for a spectral index of $\Gamma = -2.0$ (i.e. the spectral index of the source previously measured by MAGIC). This value is about a factor 3 lower than the average integral flux $F_\gamma(> 300\text{ GeV}) = (3.1 \pm 0.5) \times$

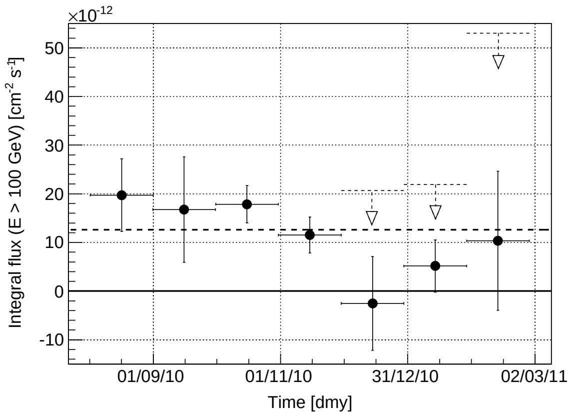

Fig. 3. NGC 1275 light curve between August 2010 and February 2011 above an energy threshold of 100 GeV, and with a month time-scale binning. No hints of variability are seen in the data. The dashed horizontal line represents the constant function resulting from the fit to the data. For the December 2010, January 2011, and February 2011 data, the upper limits on the flux above 100 GeV for a spectral index of $\Gamma = -4.0$ (calculated using the Rolke et al., 2005 method with a confidence level of 95%, and a total systematic uncertainty of 30%) are also shown (open dashed arrows).

10^{-12} cm^{-2} s^{-1} measured by MAGIC from October 2009 to February 2010 (Aleksić et al., 2010b), thereby confirming the variability of the latter source on a year's time scale.

4. Conclusions

The MAGIC telescopes have detected VHE γ-ray emission from NGC 1275, the central radio galaxy in the Perseus cluster, at a statistical significance of 6.6 σ from observations performed between August 2010 and February 2011. The corresponding average flux above 100 GeV is $F_\gamma = (1.3 \pm 0.2_{stat} \pm 0.3_{syst}) \times$

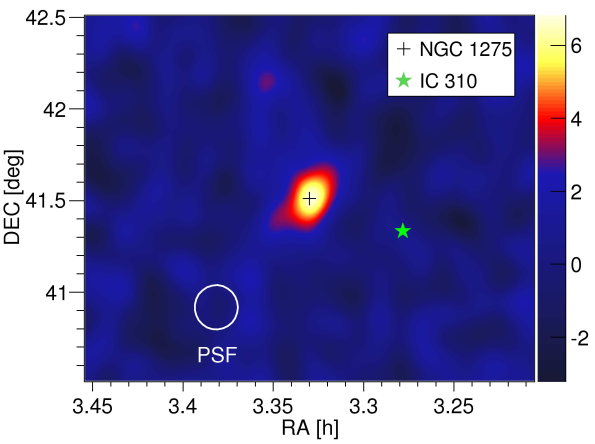

Fig. 4. Significance skymap of the central region of the Perseus galaxy cluster from 45.7 hr of MAGIC stereo observations taken between August 2010 and February 2011, above an energy threshold of 100 GeV. The NGC 1275 position is marked with a black cross, whereas the position of the radio galaxy IC 310 is shown by a green star. The PSF of about 0.12° is also displayed. The hot spot in the map at a significance level > 6 σ is consistent with a point-like emission coming from the NGC 1275 sky position.

10^{-11} cm^{-2} s^{-1}. This is the fourth nearby radio galaxy detected at VHE, after M 87 (Aharonian et al., 2003, 2006; Albert et al., 2008a; Acciari et al., 2008), Cen A (Aharonian et al., 2009), and IC 310 (Aleksić et al., 2010b). The MAGIC observation yields a spectrum that can be fitted between 70 GeV and 500 GeV by a simple power law with a spectral index of $\Gamma = -4.1 \pm 0.7_{stat} \pm 0.3_{syst}$. This result, combined with previous *Fermi*-LAT results (Abdo et al., 2009; Kataoka et al., 2010; Brown & Adams, 2011), showing a power-law spectrum with a spectral index of $\Gamma \simeq -2.1$ above 100 MeV, strongly suggests the presence of a break or cut-off around tens of GeV in the NGC 1275 spectrum. No evidence of variability on month time scale has been found above 100 GeV. Finally, the variability on a year time scale of the source IC 310 (Neronov et al., 2010; Aleksić et al., 2010b) has been confirmed. The upper limit above 300 GeV presented here is in fact about a factor 3 lower than the flux measured by MAGIC between October 2009 and February 2010.

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